An Effective Strategy to Reduce Interference: Effects of Unitization on the Development of Memory Binding

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Abstract

Memory binding is the ability to bind together multiple components in a memory trace. Previous studies have shown that one way to improve memory binding is to integrate multiple components into the same item in a meaningful way – a strategy known as unitization. To further investigate unitization as a source of development of memory binding, in terms of whether a unitization strategy has different effects on different memory structures and different age groups, the current study incorporated a semantic unitization strategy into a memory binding task and recruited multiple age groups for the experiment. Results showed that unitization led to a marked improvement in three-way binding for 7-year-olds and adults, but not for 5-year-olds, suggesting that semantic unitization could be a driving force for the development of complex memory binding in childhood and even beyond adulthood, but its effect in young children might still be limited due to their immaturity.

Keywords: unitization, memory binding, three-way binding, episodic memory, interference, memory development, semantic association

Introduction

Episodic memory is memory of an event, involving what the event is, when it happened, where it happened and so on (Tulving, 1972). An example of an eyewitness's episodic memory could be that a tall man in a dark red raincoat assaulted his victim in the parking lot at around 11 pm on a rainy Wednesday evening. In order for eyewitness testimony to be valid, one needs to successfully incorporate multiple components altogether in one account. It's easy to tell that the ability to form episodic memory correctly, or to integrate arbitrary features into one episodic representation, is a crucial capacity for human beings to function.

However, the formation of episodic memory is a tricky process, as it not only requires mnemonic discrimination of multiple elements, but it also calls for relational binding (Ngo, Lin, Newcombe, & Olson, 2019). Failure to bind the correct components in one memory trace could end up in a wrong account of the event. For instance, suppose in the aforementioned scenario, the attacker was in fact wearing a green raincoat that night, and the eyewitness happened to remember a red raincoat because a few minutes before the crime, they saw another person wearing that color and taking a brisk stroll. A wrong testimony like that could increase the chance of the criminal getting away, but unfortunately, episodic memory is proven to be fragile, because it's subject to interference from other sources (Drummey & Newcombe, 2002; Darby & Sloutsky, 2015). The ability to resist such interference and form memory binding between separate elements or features starts to develop in early childhood (Koski, Newcombe, & Olson, 2013; Ngo, Horner, Newcombe, & Olson, 2019), undergoes protracted development, and matures many years later than the ability of single item recognition (Sluzenski, Newcombe, & Kovacs, 2006). Memory development is especially prolonged when it comes to more complex memory binding, such as a three-way binding among three components, as is supported by robust evidence for development between 5 and 8 years of age (Darby, Sederberg, & Sloutsky, 2022), between 4 and 7 years of age, and between age 7 and adulthood (Yim, Dennis, & Sloutsky, 2013).

One important question about memory development is what drives memory development, or, specific to the current study, what could be a potential source of improvement of the abilities to form memory bindings. As was mentioned by Darby and Sloutsky (2022), one source of change for memory binding could be unitization, a strategy to integrate to-be-remembered components into the same item in a meaningful way (Robey & Riggins, 2018). When perceiving multiple components as part of the same item, memory will be easier because one can rely on familiarity of this single, unitized item, as opposed to deliberate recollection of a bunch of separate components and links between them. For example, in a study that used word pairs as stimuli (e.g., cloud-lawn), adults showed better recognition performance when given sentences that helped unitize words within one pair (e.g., for "cloud-lawn", it was defined as "a yard used for sky gazing") (Quamme, Yonelinas & Norman, 2007). In a more recent study that involved children as participants (Robey & Riggins, 2018), those in the unitized condition were trained to come up with a story about why the borderline of a certain color surrounds the given image. In the testing phase, children from all conditions were asked to report the borderline color of the image presented. As a result, both 6-year-old and 8-year-old children performed better at remembering the combination of

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borderline color and image in the unitized condition compared to those in the non-unitized condition.

While there were quite a few studies that investigated how unitization could strengthen two-way memory bindings, several questions remained unanswered: (1) How does unitization affect more complex memory structures such as three-way memory binding? (2) Does unitization improve memory structures of different complexity (i.e., item recognition, two-way binding, three-way binding) equally, or does the effect vary across memory structures? (3) Does unitization benefit all age groups equally, or does the effect vary across development and how?

We theorized that the effect of unitization can be generalized to three-way bindings, because successful three-way binding proves a lot harder than two-way bindings (Darby, Sederberg, & Sloutsky, 2022), and might call for unitization more than two-way binding. The goal of the present study is to examine the developmental change in memory binding ability from early childhood to adulthood, and to introduce the strategy of unitization as a scaffold in the task to see whether and how it affects children and adults' abilities to form complex memory structures. We hypothesized that (1) a unitization strategy would increase the accuracy of participants' performance on memory binding tasks across all age groups; (2) unitization would facilitate memory binding of different age groups to different extent, such that it would substantially improve the performance of older children and adults, and be of much less help to young children due to their immaturity; (3) unitization would improve different memory structures in different age groups, such that it would improve more complex memory structures like three-way binding in older children and adults, and would improve simpler memory structures like two-way bindings in young children, since two-way binding develops relatively fast in this period and falls within the zone of proximal development for them.

Method

Participants

Originally, we recruited 89 5-year-olds, 78 7-year-olds from preschools, daycare centers or elementary schools in Columbus, Ohio. After excluding 16 5-year-olds and 4 7-year-olds for not finishing the experiment, and one 7-year-old for computer failure, the actual children sample we included in our analyses consisted of 73 5-year-olds (M_{age} = 5.31 years, SD_{age} = 0.30, 34 females, 39 males) and 73 7-year-olds (M_{age} = 7.39 years, SD_{age} = 0.29, 37 females, 36 males) who were recruited from preschools, daycare centers or elementary schools in Columbus, Ohio. Also, 104 adults (M_{age} =18.93 years, SD_{age} =3.09, 80 females, 24 males) were recruited and included in this experiment, mostly from introductory psychology classes at the Ohio State University, a few from outside of the Ohio State University.

Materials

The memory binding task was adapted from a previous study and presented with OpenSesame software (Darby & Sloutsky, 2015; Darby, Sederberg, & Sloutsky, 2022; Benear et al., 2021) on a touchscreen for children, where they made responses by touching the stimuli on the screen, and on a computer monitor for adults, who made responses by clicking the mouse and keyboard.

Procedures

Participants were assigned either to the control condition[1] or to the unitization condition. In both conditions, they were instructed to perform the same memory binding task, with the only difference being that the unitization group was given a cover story that plausibly explained the binding between to-be-learned stimuli, while the control group wasn't.

The experiment included an instructional phase, a learning phase and a testing phase. In the instructional phase, participants were guided by instructions to familiarize themselves with the task. The control group was given a clear and plain instruction that their job was to remember the exact pair of color and shape that belonged with a certain cartoon character. The unitization group was told that they would hear some stories, and their job was to remember the main characters and the important objects in those stories. After that, they were given two very short stories as examples.

In the learning phase, participants were presented with 8 combinations of cartoon character, shape and color as learning materials. These 8 combinations were divided into two sets that contained 4 combinations each. Each set would be learned in a separate block. To help with the learning, participants were given a series of binary-choice tasks that repeatedly required them to choose the correct character associated with the given pair of shape and color (see the learning phase in Figure 1) between Winnie the Pooh (represented as X in all figures) and Mickey Mouse (Y), and after they made a response, they would be given feedback regarding whether their response was correct. As was mentioned before, the control group was only given a plain instruction about how to proceed with the task, while the unitization group was presented with stories that involved the characters and their corresponding shapes and colors. In addition, when performing the binary-choice tasks, the unitization group was guided by scaffolding questions framed based on the story plot (e.g., "Who looked under this carpet?") for the first half of their learning of each set of materials, in order to rehearse the semantic bindings between stimuli. The question was taken away later so the unitization group had to rely on the visual stimuli just like the control group had been doing all along.

[1] Five-year-olds' and adults' data in this condition were partially from the same dataset used in a previous CogSci publication by Wang, Gao and Sloutsky in 2023.

In the testing phase, participants were given one cartoon character and five pairs of shapes and colors, and were required to choose one color-shape pair that belonged in the same story with the given character. Either the five color-shape pairs shared the same color as the cue but varied in shapes, in which case participants were supposed to make judgments based on shapes (testing phase in Figure 1), or the five options shared the same shape as the cue but varied in colors, with color being the tested feature instead. Among the five pairs of shapes and colors, only one pair served as the correct answer, and the other four were distractors.

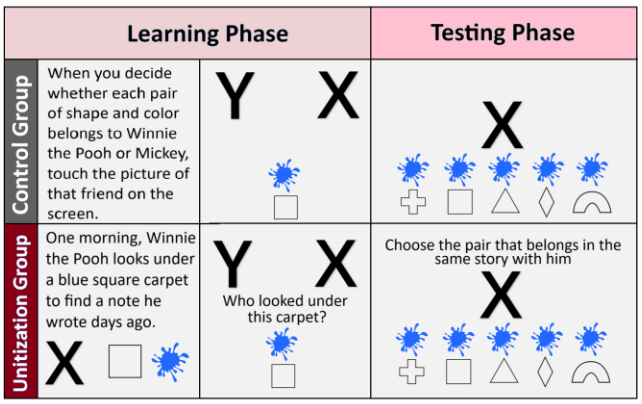

Figure 1: Major experimental procedures in control group and unitization group

The stimuli in the learning phase and options in the testing phase were designed in such a way that different levels of memory structures (i.e., three-way binding, two-way binding, single item familiarity) could be measured. Details of this design were spelt out in previous publications (Darby, Sederberg, & Sloutsky, 2022; Wang, Gao, & Sloutsky, 2023), but briefly speaking, the 8 combinations overlapped one another to different degrees, and the minimum requirement for identifying each of them correctly in the test phase could be different levels of binding, i.e., some strictly required three-way binding and some only needed two-way binding.

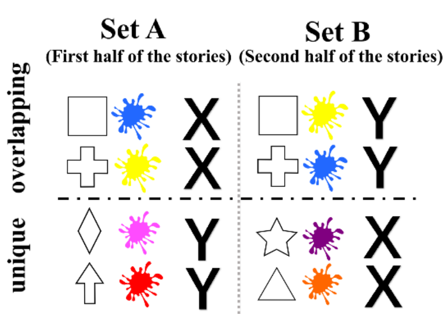

Figure 2. Example of a complete set of learning materials in one entire learning phase

For example, Figure 2 is a plausible set of learning materials in the learning phase. The red-arrow-Y combination (Figure 2, left down corner) is easier to retrieve in a testing trial, as the red color and the arrow shape have only been seen associated with each other. Forming two-way bindings between items, such as a red-arrow combination, will suffice to identify the correct option from the options, since there are no other shapes linked with red, or other colors linked with arrow in the learning materials. However, a recognition task on the blue-square-X combination is not so easy (Figure 2, left upper corner), because color blue is not only associated with square in one combination, but it's also associated with a cross in a different combination (Figure 2, right upper corner). If you only form a two-way binding between shape and color (i.e., item-item binding), you will find the blue-square pair and the blue-cross pair equally feasible in the testing trial from Figure 1; similarly, if you only form a two-way binding between the tested feature and the character (i.e., item-character binding), you will find both cross-X and square-X to be plausible, and still have no way of ruling out the cross in the testing trial. The only way to identify the correct option is through a three-way binding between blue, square and X. Stimuli that strictly required three-way binding were classified into overlapping condition, and those only required item-item binding were the unique condition. These two conditions were within-subject.

As for the five options in a trial in the testing phase, one option served as the correct response, one contained a distractor feature that came from the overlapping condition (overlapping feature), one contained a distractor feature that came from the unique condition and was associated with the same character (unique same character feature, or unique same in short), one contained a distractor feature from the unique condition which was associated with a different character (unique different character feature, or unique different in short), and one contained a novel feature that had not appeared in the learning phase at all. Ruling out each distractor would require different levels of memory structures, and mistaking one of the distractors as the correct option would mean failing at forming memory structures at certain levels (see the following section for details).

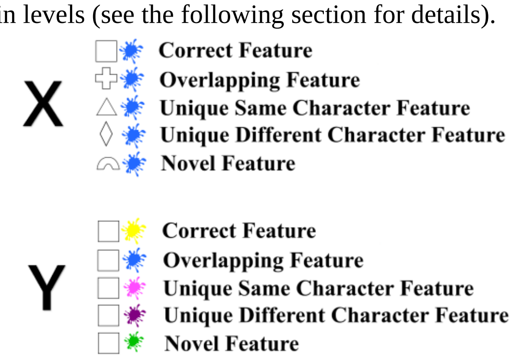

Figure 3. Response types in testing phase

Analysis

To unentangle participants' memory processes underlying their responses in this task, a Multinomial Processing Tree (MPT) model was employed (Figure 4), in which different levels of memory structures were represented as different parameters, ranging from 0 to 1. A total of 4 memory processes were involved in this model, including three-way binding (b), two-way item-item binding (ii), two-way item-character binding (ic), and single-item familiarity (f).

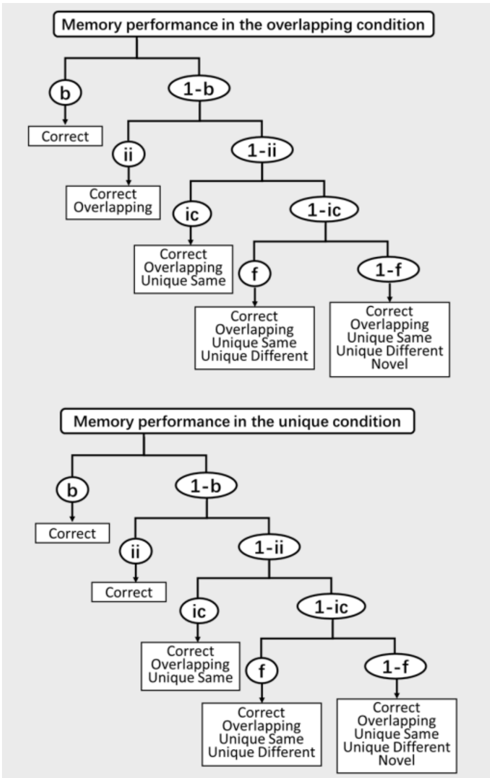

Figure 4: Structures of the MPT model in different conditions.

The model illustrates how memory processes lead to different responses in the testing phase using four memory parameters (b, ii, ic, f). In the overlapping condition, the branch of "b" represents success in forming three-way binding, which leads to the correct response, while the branch of "1-b" represents failure to do so, which makes it necessary to discuss other possibilities, such as success in forming item-item binding ("ii", in which case participant's choice will come down to the correct and overlapping response), or failure to do so ("1-ii"). In the unique condition, both "b" and "ii" lead directly to the correct response, since the binding between items is sufficient. When there are multiple responses at the end of a branch, each response has an equal probability of being produced. Each failure at forming a memory structure at a certain level will lead to more response types being confused as plausible candidates along with the correct response. Ultimately, if a participant fails to achieve even single-item familiarity, all five options will be equally plausible to them.

Results

Learning Phase

First, we conducted a series of One-Sample t-test to examine whether participants showed above-chance accuracy in the learning phase. As shown in the Figure 5, all age groups achieved significantly above chance accuracy in the learning phase, all *p*s < 0.001, all *t*s > 6.97. Second, we conducted a three-way mixed ANOVA with age and group as between-subject independent variables and condition as a within-subject variable. We found a main effect of age, $F(2, 486) = 21.88$, $p < 0.001$, and post-hoc pairwise comparison showed that while 7-year-olds significantly outperformed 5-year-olds, $p < 0.001$, there was no significant difference between the performances of 7-year-olds and adults, $p = 0.513$. We also found a main effect of group, such that the unitization group significantly outperformed the control group, $F(1, 486) = 138.30$, $p < 0.001$. We did not find main effect of condition, meaning that participants performed comparably in overlapping and unique conditions in the learning phase, $F(1, 486) = 1.25$, $p = 0.265$, nor did we find any interaction between variables, *F*s < 0.82, *p*s > 0.443.

Given the overall high accuracy shown in the learning results from the unitization group across different ages, the stories in the learning phase proved comprehensible to both children and adults, and the training proved effective. To examine the developmental changes in memory structures of different complexities, and the effect of unitization on different age groups, we conducted analyses on participants' responses in the testing phase.

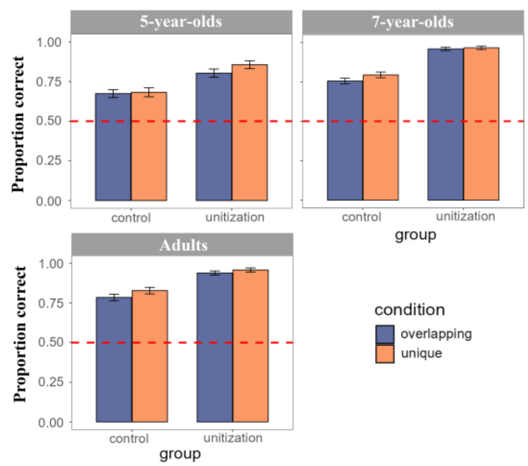

Figure 5: Participants' performance in the learning phase

Testing Phase

Behavioral results A mixed three-way ANOVA showed that there was a significant effect of group on the proportion of correct responses in the testing phase, such that participants from the unitization group gave more correct responses compared to those from the control group, $F(1,244) = 68.23$, $p < 0.001$. Post-hoc pairwise multiple comparison showed that this effect of group was robust for 7-year-olds (M_{con} =0.40, SD_{con} =0.24; M_{uni} =0.67, SD_{uni}=0.23) and adults (M_{con} =0.52, SD_{con} =0.27; M_{uni} =0.75, SD_{uni}=0.25), *p*s < 0.001, but nonsignificant for 5-year-olds (M_{con} =0.30, SD_{con} =0.21; M_{uni} =0.43, SD_{uni}=0.25), $p = 0.052$. There was also a significant condition effect on the proportion of correct responses in the testing phase, such that participants gave more correct responses in the unique condition (*M* =0.60, *SD* =0.31) compared to the overlapping condition (*M* =0.45, *SD* =0.25), $F(1,244) = 110.75$, $p < 0.001$. There was also a significant age effect on correct responses, $F(2,244) = 49.34$, $p < 0.001$. Post-hoc analyses revealed that while 7-year-olds (*M* =0.67, *SD* =0.23) were more accurate than 5-year-olds (*M* =0.43, *SD* =0.25) in the unitization group, $p < 0.001$, 7-year-olds and adults were comparably accurate in both control group (M_7 =0.40, SD_7 =0.24; M_{adult} =0.52, SD_{adult}=0.27) and unitization group (M_7 =0.67, SD_7 =0.23; M_{adult} =0.75, SD_{adult}=0.25), *p*s > 0.081. Additionally, there was an age-by-condition interaction, $F(2,244) = 9.08$, $p < 0.01$, such that in the overlapping condition, the age-related difference in accuracy existed between 7-year-olds and adults ($p < 0.05$), not between 5-7 years of age ($p = 0.068$); but in the unique condition, the age-related difference existed between 5-7 years of age ($p < 0.001$), not between 7-year-olds and adults ($p = 0.36$).

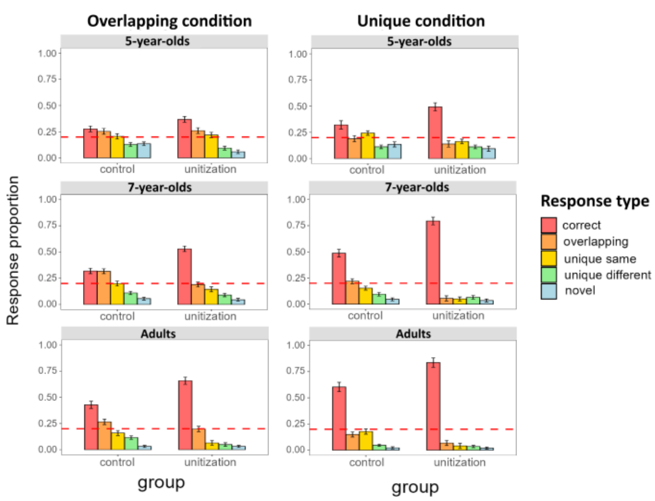

Figure 6: Response patterns of each age group in the testing phase

To sum up, the analyses of the behavioral patterns revealed developmental changes in memory accuracy, and how those changes differed between memory tasks in different conditions. The analyses also showed the effectiveness of the unitization strategy, except for 5-year-olds. However, these surface-level analyses couldn't tell us how the underlying memory processes were improved with age or unitization. In order to gain more insights into how unitization affects memory development in terms of different levels of memory structures, we needed computational modeling to disentangle memory structures as parameters and conduct analyses on each parameter.

Modeling results we fit an MPT model to the responses of each age group, and the results were shown in Table 1 and visualized in Figure 7.

Table 1. 95% Highest Density Interval of the posterior distribution of the memory parameters

	b	ii	ic	f
5-yo control group	[0.06,0.34]	[0.07,0.52]	[0.14,0.62]	[0.15,0.65]
5-yo unitization group	[0.08,0.69]	[0.07,0.76]	[0.16,0.77]	[0.20,0.67]
7-yo control group	[0.08,0.30]	[0.08,0.73]	[0.14,0.74]	[0.18,0.65]
7-yo unitization group	[0.17,0.71]	[0.19,0.70]	[0.18,0.59]	[0.27,0.62]
adult control group	[0.08,0.71]	[0.09,0.76]	[0.18,0.74]	[0.26,0.67]
adult unitization group	[0.15,0.87]	[0.12,0.79]	[0.20,0.71]	[0.25,0.59]

Firstly, in order to gain insights into the developmental trajectories of different memory structures, we looked into the control group by running one-way ANOVA for each memory parameter, using age as the independent variable. Our results showed significant developmental differences in all memory parameters (b: $F(2,244) = 10.56$, $p < 0.001$; ii: $F(2,244) = 6.78$, $p < 0.005$; ic: $F(2,244) = 7.30$, $p < 0.005$; f: $F(2,244) = 13.71$, $p < 0.001$). While older age groups had a general tendency to outperform younger age groups, the rate of development differed between memory parameters. Specifically, there was a significant difference in three-way binding between 7- year-olds and adults, $p < 0.005$**,** but no significant difference between 5- and 7-year-olds, $p = 0.41$. However, for item-item binding, item-context binding and item familiarity, there was a significant difference between 5- and 7-year-olds, *p*s < 0.05**,** but not between 7-year-olds and adults, *p*s > 0.31.

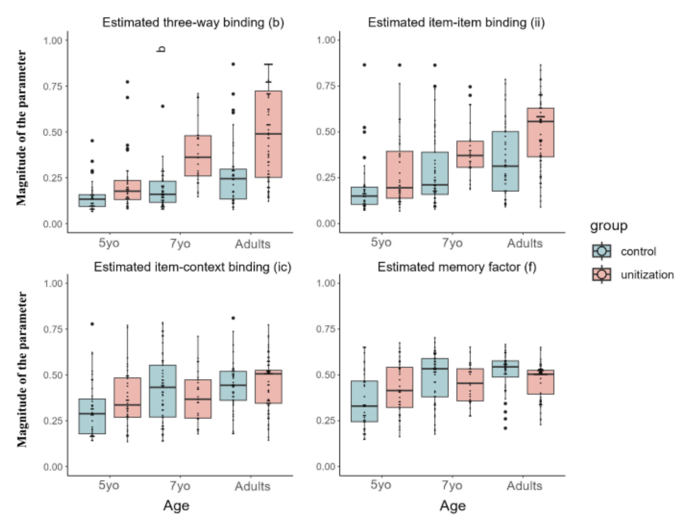

Figure 7. Estimates of the memory parameters

Secondly, we conducted two-way ANOVA for each memory parameter, with age and group being the independent variables. According to the analyses, the effects of group showed different patterns between memory parameters. For three-way binding, the main effect of group was significant, $F(1,244) = 57.98$, $p < 0.001$, as well as the age-by-group interaction, $F(2,244) = 4.63$, $p < 0.05$. Post-hoc analyses with Tukey's Test showed that 7-year-olds and adults from the unitization group were able to achieve stronger three-way binding compared to the control group at their own age, *p*s < 0.001, but this effect of unitization was not detected at age 5, $p = 0.529$. For item-item binding, there was an effect of unitization, $F(1,244) = 27.26$, $p < 0.001$, but when broken down to each age level, the effect was only significant for adults, $p < 0.001$. For both item-context binding and item familiarity, the effect of unitization was nonsignificant, $F(1,244) = 0.28$, $p = 0.595$, $F(1,244) = 0.14$, $p = 0.712$.

Discussion

To recap the findings, we found age-related differences in different levels of memory structures. Specifically, in terms of three-way binding, an age effect was present between age 7 and adulthood, and absent between age 5 and 7; for less complex memory structures like item-item binding, item-context binding and item familiarity, the pattern was the opposite, such that there was an age effect between 5 and 7, but not between 7 and adulthood. This result is partially consistent with previous findings that the abilities to form simpler memory structures have earlier onsets and develop fast in early childhood, whereas the abilities to form complex memory structures such as three-way binding develops much more slowly and doesn't reach maturity until adulthood (Sluzenski, Newcombe, & Kovacs, 2006; Yim, Dennis, & Sloutsky, 2013; Darby & Sloutsky, 2015). However, the absence of difference in three-way binding between age 5 and 7 contradicted previous research which found substantial development in this ability in early childhoold (Yim, Dennis, & Sloutsky, 2013; Darby, Sederberg & Sloutsky, 2022). One possible reason is the survivorship bias due to the relatively high dropout rate of 5-year-olds in the control group of this study. In other words, those 5-year-olds who actually made it to the end might possess longer attentional span and working memory capacities.

More intriguingly, we found effects of unitization on memory binding and how such effects differed between age groups and memory structures. Specifically, the unitization strategy proved very helpful to the memory performance of 7-year-olds and adults, given the striking improvement from the control group to the unitization group. This is consistent with previous findings that unitization improves relational memory in both children and adults by integrating separate memory elements in a meaningful way (Robey & Riggins, 2018; Quamme, Yonelinas, & Norman, 2007), and more importantly, our finding extended this line of research by replicating the unitization effect on more complex memory structures. However, contrary to previous research which proved unitization strategies effective for young children (Robey & Riggins, 2018), we failed to find any effect of unitization for 5-year-olds in the behavioral and modeling results of the testing phase; the only significant advantage they achieved from unitization was in the learning phase. One possible reason is that 5-year-olds lacked the overall hippocampal maturity to achieve memory binding and successfully retain it over time (DeMaster, Pathman, Lee, & Ghetti, 2014), therefore, the unitization strategy gave them an edge in the learning phase earlier, but not in the testing phase later. Another possible reason can be that while 5-year-olds could successfully identify the main characters of the stories in the learning phase, it remained challenging for them to tell apart highly similar memory traces in the testing phase, due to the immaturity of dentate gyrus, which is a later-maturing subfield of hippocampus and plays an important role in the ability to transform similar memory traces into distinct ones, otherwise known as pattern separation (McClelland, McNaughton, & O'Reilly, 1995; Lavenex & Banta Lavenex, 2013). An additional explanation can be that 5-year-olds lacked knowledge and language skills to integrate those multiple components semantically.

Contrary to our prediction, we didn't find the effect of unitization in any two-way binding structures in children, yet we found improvement in adults' item-item binding. This could be a limitation of our task, such that our cover stories might not have displayed a sufficiently vivid semantic association between stimuli for children (e.g., "Winnie the Pooh looks under a blue carpet", but why a "blue carpet"? What's the association between "blue" and "carpet"?), while adults could join two items into one even just with a loose association. Also, this null effect in two-way binding in children might be a result of the between-subject design in this study. Future studies may consider a within-subject design in order to reduce individual differences between groups.

In conclusion, the current study partially replicated the effect of unitization on memory binding, and extended existing research in memory development by studying the effect of unitization on complex memory binding, as well as comparing the effect of unitization across different memory structures in multiple age groups across development. Besides supporting the idea that unitization can be a driving force for the development of memory binding, our findings also suggest that when it comes to scenarios that require complex memory binding, semantic unitization strategies might only be helpful to older children (above the age of 6-7) and adults; as for what strategies would help young children form complex memory binding, it can be a direction for future studies.

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